

# The Pierre Auger Observatory: Latest results of the mass composition and upgrade plans

Alexander Herve | 2. March 2015

KARLSRUHE INSTITUTE OF TECHNOLOGY



www.kit.edu

PIERRE AUGER

# Ultra-high energy cosmic rays





- Energies above 10<sup>18</sup> eV
- Low intensity: 1 per 100 km<sup>2</sup> above 10<sup>19</sup> eV
- CM energies larger than that achievable at the LHC

Cosmic Rays

The Pierre Auger Observatory

Latest Results

Upgrade 0000 Summary

Alexander Herve - Latest results of the mass composition and upgrade plans

2. March 2015 2/23

# **Questions for UHECR**



#### Answered

- Is there a flux suppression at the highest energies?
- Is there any anisotropy?

#### Yet to be unanswered

- Origin of cosmic rays?
- What are they?
- Can we extrapolate the hadronic models to the highest energies?

Cosmic Rays	The Pierre Auger Observatory	Latest Results	Upgrade	Summary
Alexander Herve – Latest results of the mass composition and upgrade plans		2. March 2015	3/23	

# The Pierre Auger Observatory



- Surface detector: 1600 water Cherenkov detectors across 3000 km<sup>2</sup>
- Fluorescence detector: 24+3 telescopes of 30° x 30° FOV



Cosmic Rays

The Pierre Auger Observatory

Latest Results

Upgrade Summary

Alexander Herve - Latest results of the mass composition and upgrade plans

#### **Surface Detector**





- Measures lateral density of particles at ground
- 100% duty cycle
- Energy threshold: 3 EeV (full efficiency up to 60°)
- Geometrical aperture

Alexander Herve – I	atest results of the mass composition and upo	irade plans	2 March 2015	5/23
	0000	0000000000	0000	
Cosmic Rays	The Pierre Auger Observatory	Latest Results	Upgrade	Summary

#### **Fluorescence Detector**





- Measures UV photons emitted by de-excitation of N<sub>2</sub>
- Calorimetric energy measurement
- Lower energy threshold
- 15% duty cycle

#### Hybrid detection





#### Data driven calibration

Cosmic Rays	The Pierre Auger Observatory	Latest Results	Upgrade	Summary
Alexander Herve - Latest	results of the mass composition and upgrade pl	ans	2. March 2015	7/23







- Quality cuts applied to obtain well reconstructed profiles
- Fiducial volume cut to allow for unbiased data set
- Uncertainties in  $\langle X_{\rm max} \rangle$  due to reconstruction, event selection and atmospheric conditions are below 15 g/cm<sup>2</sup>

Cosmic Rays	The Pierre Auger Observatory	Latest Results	Upgrade 0000	Summary
Alexander Herve - Late	est results of the mass composition and upgr	rade plans	2. March 2015	8/23

#### **Latest Results**





Interpretation of results depends on hadronic interaction model

Trend towards heavier mass at higher energies

Cosmic Rays	The Pierre Auger Observatory	Latest Results	Upgrade 0000	Summary
Alexander Herve - Lates	results of the mass composition and upgrad	de plans	2. March 2015	9/23

#### In A





Cosmic Rays

The Pierre Auger Observatory

Latest Results

Upgrade 0000 Summary

Alexander Herve - Latest results of the mass composition and upgrade plans

2. March 2015

10/23

# $X_{\rm max}$ distributions





Analysing just the first two moments could lead to degeneracies.

 By using the full X<sub>max</sub> distribution, sensitivity of the shape in maintained and further information of the composition can be retrieved.

Cosmic Rays	The Pierre Auger Observatory	Latest Results	Upgrade	Summary
	0000	000000000	0000	
Alexander Herve - Latest r	esults of the mass composition and upgrade p	lans	2. March 2015	11/23

#### **Fraction fitting**





- Decreasing proton fraction as energy increases.
- Very small to no iron fraction.

Cosmic Rays	The Pierre Auger Observatory	Latest Results	Upgrade	Summary
	0000	0000000000	0000	
Alexander Herve - Latest	esults of the mass composition and upgrade p	lans	2. March 2015	12/23

## **Fraction fitting**





Two component fit does not reproduce the data for any model.
Proton fraction consistent between models. Difference in intermediary masses.

Cosmic Rays	The Pierre Auger Observatory	Latest Results	Upgrade	Summary
Alexander Herve – Latest r	esults of the mass composition and upgrade p	ans	2. March 2015	13/23

## **Fraction fitting**





#### Almost no iron for both three and four component fits.

Cosmic Rays	The Pierre Auger Observatory	Latest Results	Upgrade 0000	Summary
Alexander Herve - Latest re	esults of the mass composition and upgrade pl	ans	2. March 2015	14/23

## Muon production depth





Uses timing information from SD traces

- Can reconstruct muon production depth distribution
- heta between 55 $^\circ$  and 65 $^\circ$

Cosmic Rays	The Pierre Auger Observatory	Latest Results	Upgrade	Summary
	0000	000000000000000000000000000000000000000	0000	
Alexander Herve – Latest	results of the mass composition and upgrade p	lans	2. March 2015	15/23

## Muon production depth





## Mean number of muons





- Fit muon density map to data
- Lateral shape of density map consistent between models
- heta between 62 $^\circ$  and 80 $^\circ$

Cosmic Rays	The Pierre Auger Observatory	Latest Results	Upgrade	Summary
	0000	0000000000	0000	
Alexander Herve - Latest	esults of the mass composition and upgrade p	lans	2. March 2015	17/23

#### Mean number of muons





• Use ratio  $\langle R_{\mu} \rangle / \langle E/10^{19} \text{eV} \rangle$  to cancel out energy scaling

- Discrepancy between models and data
- No model can describe both  $\langle R_{\mu} \rangle$  and  $\langle X_{\max} \rangle$

Cosmic Rays	The Pierre Auger Observatory	Latest Results	Upgrade	Summary
	0000	0000000000	0000	
Alexander Herve - Latest r	esults of the mass composition and upgrade p	lans	2. March 2015	18/23

# Enhanced muon sensitivity



- Increased  $e/\mu$  separation in surface array
- Factor pprox 10 in statistics for composition measurements
- Lower requirement of models for interpretation of composition results
- Tension in current muon measurement results as no model is in agreement with all studies

Alexander Herve – Latest results of the mass composition and upgrade plans			2. March 2015	19/23
	0000	00000000000	<b>•0</b> 00	
Cosmic Rays	The Pierre Auger Observatory	Latest Results	Upgrade	Summary

## Science case for upgrade



- Identify origin of flux suppression: GZK vs Maximum energy scenario
- Search for contribution of protons at highest energies
- Study extensive air showers and hadronic physics above  $\sqrt{s} = 70$  TeV

Need event-by-event composition in flux suppression region!

Cosmic Rays	The Pierre Auger Observatory	Latest Results	Upgrade	Summary
	0000	0000000000	0000	
Alexander Herve - Latest results of the mass composition and upgrade plans			2. March 2015	20/23



- 4 m<sup>2</sup> scintillator on top of SD
- Prototype already in field

$$egin{array}{c} \left[ egin{array}{c} S_{Scin} \ S_{WCD} \end{array} 
ight] = \left[ egin{array}{c} a_{em} & a_{\mu} \ 1-a_{em} & 1-a_{\mu} \end{array} 
ight] \left[ egin{array}{c} S_{em} \ S_{\mu} \end{array} 
ight]$$

Cosmic Rays

The Pierre Auger Observatory

Latest Results

Upgrade Summary 0000 2. March 2015 21/23

Alexander Herve - Latest results of the mass composition and upgrade plans

## AMIGA-Grande





- Buried scintillators to measure muons
- 7 stations are currently deployed
- More stations are planned

 Cosmic Rays
 The Pierre Auger Observatory
 Latest Results
 Upgrade
 Summary

 Alexander Herve – Latest results of the mass composition and upgrade plans
 2. March 2015
 22/23

# **Summary and Outlook**



- Latest mass composition results continue to show a changing composition.
- Fitting fractions to X<sub>max</sub> distributions show a decreasing proton fraction, negligible iron fraction.
- Enhanced muon detection is of great importance to help understanding of models and interpretation of measurements.
- Composition enhanced anisotropy would also be possible.
- Upgrades are undergoing preliminary testing and full deployment will start soon.

Cosmic hays		0000000000	0000	Summary
Alexander Herve – Latest results of the mass composition and upgrade plans			2. March 2015	23/23

## **Latest Mass Composition Papers**



- Depth of maximum of air-shower profiles at the Pierre Auger Observatory. I. Measurements at energies above 10<sup>17.8</sup> eV Physical Review D 90, 122005 (2014)
- Depth of maximum of air-shower profiles at the Pierre Auger Observatory. II. Composition implications Physical Review D 90, 122006 (2014)
- Muons in air showers at the Pierre Auger Observatory: Measurement of atmospheric production depth Physical Review D 90, 012012 (2014)
- Muons in air showers at the Pierre Auger Observatory: Mean number in highly inclined events
   Physical Review D 91, 032003 (2015)

#### Thank You

## **Fiducial FOV**





Alexander Herve - Latest results of the mass composition and upgrade plans



#### $X_{\rm max}$ cross checks



